THE RELATIVE EFFECTS OF CONVECTION AND RADIATION HEAT TRANSFER ON THE THERMAL SENSATIONS OF SEDENTARY SUBJECTS

by

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INTRODUCTION

The demands and requirements for human comfort are continually expanding in the modern society. This increase in demand is accompanied by an increase in need for scientists and engineers who can properly define the requirements to provide human comfort and who can develop the means for obtaining them.

A major portion of the comfort concept is thermal comfort; i.e. man's satisfaction with his thermal environment. Development of criteria for thermal comfort involves knowledge of the physiological indices of thermal comfort and understanding of the heat transfer relationships between man and his environment.

Thermal comfort is a complex concept involving many and diverse parameters. However, the fundamental cause - effect relationship can be expressed simply as the state of mind resulting from the interplay of the many variables involved in physiological and heat transfer processes. The state of mind referred to is basically composed of two parts: "thermal sensations" and "comfort sensations". Research in the field of thermal comfort essentially revolves about the principle of defining the true character of the interplay of the biological and environmental variables and the concomitant effect on "thermal" and "comfort sensations".

The present study is intended to provide an analysis of the relative effects of two environmental factors, convection and radiation heat transfer, on the "thermal sensations" of seden-

tary subjects. It is necessary to make the reasonable assumption that a person's thermal sensations are governed by the same physical laws that govern heat loss from the body to further establish the relative values of the convection and radiation heat transfer coefficients. With the preceding information it is possible then to establish a zone of thermal neutrality (where subjects feel the environment is neither too cool nor too warm) which is a function of mean radiant temperature (MRT)* and air temperature.

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*MRT - the temperature of a uniform black enclosure in which an occupant would exchange the same amount of radiant heat as in the existing nonuniform environment.

LITERATURE REVIEW

As man has progressed in knowledge and scientific endeavor, he has become better equipped to investigate his thermal environment. Certainly there has always been an awareness of the ability to overcome severe environments, but with the industrial revolution came the need and ability to describe the thermal environment quantitatively as was being done with many physical entities. As early as 1733 there was evidence of concern with three dominant parameters (air temperature, moisture, and velocity) of the thermal environment in the explanation of Arbuthnot that the chilling effect of the wind is due to the dispersing of the layer of warm, moist air that invests the body. In 1804, Sir John Leslie, concerned with measuring the cooling effect of the wind, incorporated an alcohol thermometer with a large bulb that was warmed before inserting into a stream of air to assess the wind speed by the rate of cooling sensed by the bulb.

One remaining dominant parameter of the thermal environment, the radiant heat transfer, was the concern of Tredgold in 1824. Tredgold, a pioneer of central heating, realized that a lower air temperature was possible in a dwelling when heated by an open fire than when only the air was warmed. He explained that objects that receive heat from the fire were always warmer than the air. This reasoning apparently pervaded the thoughts of the General Board of Health (England) when they set forth as part of the requirements for comfort that the walls of a dwelling

should be at a temperature at least as high as the general temperature, thus cold walls as a cause of discomfort were officially recognized. An instrument was devised by Aitken in 1887 to show the effects of radiation as tempered by the wind. He used a blackened, hollow metal sphere six inches in diameter with the bulb of a thermometer placed at the center to estimate combined effects of solar radiation and wind. He apparently did not adapt the instrument for use in indoor environments.

In 1844, Reid and Bernan were concerned with humidity level required for comfort, particularly in winter. At this time there was still considerable doubt as to the true understanding of ventilation requirements. This was partly due to the feelings of some very reputable scientists, notably Lavoiser and Pettenkofer, that stuffiness and discomfort noted in the dwellings and buildings of that time were due to the chemical properties of the environment, directly or indirectly traceable to the presence of the carbon dioxide in the air. However, Lablanc held that proper ventilation was needed for the thermal properties of the air, or in other words, to provide the necessary heat transfer to keep inhabitants comfortable. Near the turn of the century, Hermans (1883) and Fluge and his associates (1905) had accumulated evidence to overwhelmingly support the contention that thermal properties are more important than chemical properties, and that feelings of freshness were due largely to more effective cooling.

The pioneering research work of the 19th century in the

field of human comfort culminated in the forming of A.S.H.V.E.* in 1894. The Society at that time was, for obvious reasons, principally concerned with heating and ventilating processes to obtain comfort.

In the years following the formation of A.S.H.V.E., one of the first attempts to catalogue and understand several properties of man's thermal environment was made by Dr. E. Vernon Hill. He developed the synthetic air chart, a means of establishing the wet bulb temperature of the environment as the controlling or dominant factor for comfort. This no doubt was a reaction to the previous inadequate theories that dry bulb temperature alone determined necessary conditions for comfort. The ensuing exchange of opinions and critical discussions between Dr. Hill and others (including Dr. W.H. Carrier) who felt that both wet bulb and dry bulb temperatures were necessarily involved in describing comfortable environments brought a general awakening of interest in the field. The interest was fueled by the heat transfer analysis of Dr. Leonard Hill. He developed the kata thermometer for the purpose of expressing the combined effects of the major thermal environmental factors - air temperature, relative humidity, air velocity, radiant temperatures - on heat loss from the human body. The highlight of this period in comfort research was the establishment of the A.S.H.V.E. Research Laboratory in

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*American Society of Heating and Ventilating Engineers, changed to American Society of Heating, Refrigerating, and Air Conditioning Engineers (A.S.H.R.A.E.) in 1959.

1919. At that time, Professor John Sheppard at Teacher's Normal College introduced the term comfort zone which more or less marks the emergence of comfort research into the modern era.*

Since the development of the phrase "comfort zone", there has been difficulty in establishing a clear, concise definition of the term. Leopold (52) felt that building up comfort was a very nebulous condition, however, many researchers have offered definitions of comfort of which the following are examples:

Glickman (26) - A derived state of feeling based upon a physiological balance of the individual to his environment wherein the stimuli are of low intensity.

Leopold (52) - The absence of discomfort or annoyance due to temperature and atmospheric effects indoors.

Nevins (61) - Criteria for thermal comfort are specifications for the indoor environment in which an arbitrary percentage of the occupants will express thermal comfort.

Many researchers agree that comfort is nebulous, a combination of physical, physiological and psychological reactions for which exact determination is impossible. An attempt to control the variances due to these varied reactions in the results of this study are discussed in the Experimental Design.

From this point the research efforts multiply many times in number and diversity. The first work of Houghton and Yaglou (41) (42) established lines of equal comfort, defined effective

*The preceding summary has been generally adapted from Bedford (3), Nevins (62), and Houghton, et al. (39) who are themselves respected researchers in the area of human comfort.

temperature, and determined a comfort zone. These experiments were conducted under dynamic conditions, with the subjects walking from one controlled room (air temperature and humidity constant) to another. The conditions of the second room were adjusted until the instantaneous reactions of the subjects to the second room were ones of identical comfort sensations or equal warmth. The results plotted on a psychrometric chart were called lines of equal warmth. The effective temperature (ET) was defined as an arbitrary index which incorporates into a single figure the effects of air temperature, humidity, and air velocity on thermal sensations determined in the above experiments. The numerical value of ET is that temperature of still, saturated air that evokes feelings of equal warmth (constant thermal sensation). Separate comfort zones were developed for summer and winter seasons. The conclusions of this study were altered in succeeding years by various investigators (Yaglou (78), Glickman (26), Nevins, et al. (63), McNall, et al. (60)) who have determined that for extended exposures of at least one hour, ET overestimates the effect of humidity on comfort and that very few real differences exist between reactions to similar environments in winter and summer. It was also felt by Leopold (52) that the comfort zones were too wide to be practical in that they included such a range of conditions that only 50% of the people involved would be comfortable.

At this time (1930's) in the development of comfort research a very concerted and concise series of studies was initiated at

the John B. Pierce Laboratory of Hygiene, New Haven, Connecticut. By exposing relatively few subjects to many different environments and through the use of a technique of partitional calorimetry, extensive quantities of data were compiled concerning the total thermal environment (Winslow, et al. (73)). Subsequently, effects of air temperature, humidity, air movement, and radiant temperature on heat transfer for nude semi-reclining subjects were evaluated (72) (76) (77) (78). A single parameter, operative temperature, was developed by the group at the Pierce laboratory (17). The operative temperature accounted for the effects of air temperature, air velocity, and MRT on the heat loss from the human body. The operative temperature concept has recently been expanded by Gagge, Rapp, and Hardy (21) (22), to include thermal exchange with high-temperature sources of radiant heat. Lines of constant operative temperature on the MRT - air temperature plane show the relative effects of convection and radiation heat transfer from human subjects particularly for subjects that are thermally neutral as shown in Figure 4.

Many other researchers have conducted extensive, definitive tests on heat transfer from human subjects and determination of comfort zones. After the establishment of the new A.S.H.R.A.E environmental test chamber in Cleveland, Koch, Jennings, and Humphreys (50) conducted a study which showed the effects of relative humidity to be small on the thermal sensations of sedentary, lightly clothed subjects. When the A.S.H.R.A.E. environmental facility was relocated at Kansas State University

in 1963, studies were conducted to establish conditions of air temperature and relative humidity for thermal comfort at several distinct levels of activity (58) (63). At this time a distinction between comfort sensations and thermal sensations was effected to better describe the response of the subject to his environment; that is, the response can be thermal (either warmer or cooler sensations relative to thermally neutral) or comfortable (a more "general" description of the total comfort response). A recent study by Fanger (12) at the K.S.U. - A.S.H.R.A.E. facility establishes a Basic Comfort Equation, which included all factors of the thermal environment affecting the heat transfer of subjects that are thermally neutral. This equation (after further confirmation and refinement by more thorough testing) will permit a complete, inclusive treatment of human comfort in an engineering manner.

In addition to the work at the Pierce and A.S.H.R.A.E. laboratories, a fine study by Nielsen and Pedersen (64) established equations for determining lines of equal heat loss for clothed subjects for combinations of MRT and air temperature. Their results for thermally neutral subjects are shown in Figure 4.

Many studies in specific phases of the total thermal comfort area have been conducted. Representative of these are analyses of respiratory heat exchange (2) (54), evaporative (sweat) loss (59) (74), metabolic heat production (31) (59) (74), the diffusion of water vapor through the skin (6), effect of

clothing (20) (46), effective convection and radiation surface areas (23) (28) (64), and convection and radiation heat exchange (31) (64) (76) (79).

The results of this study are expected to support and expand existing knowledge relative to radiation and convection heat exchange for sedentary clothed subjects who are thermally neutral.

METHODS

Experimental Design

Many studies have been made with the intention of delineating the relative effects of the three main avenues of heat transfer (evaporation, radiation, convection) for a person experiencing thermal comfort. Much of the previous research (64) (74) (75) has been conducted on relatively few subjects who were exposed to many combinations of those factors affecting their thermal sensations. It was the intention of the present study, however, to expose a relatively large number of subjects to a discrete set of environments where all but two environmental variables are maintained constant so that a meaningful statistical analysis could be made of the subjects' "thermal sensation" responses to changes in only those two environmental variables. Previous use of this technique by Nevins, et al. (63) and McNall, et al. (58) has produced evaluation of the relative effects of atmospheric moisture and air temperature on thermal sensations of sedentary and active persons, and zones of thermal neutrality have been established for several distinct levels of activity. These methods also produce necessary estimates of the variation expected in the reactions of large numbers of subjects to similar environments.

In the present investigation, the relative effects of radiation and convection heat transfer on thermal sensations are shown by statistically analyzing the "thermal sensation" re-

sponses of many subjects to environments of different combinations of MRT and air temperature. All other variables affecting thermal sensations, insofar as possible, were held constant. In addition, the results of this investigation include the development of a zone of thermal neutrality as a function of MRT and air temperature for a near-symmetric radiant temperature distribution (wall, floor, and ceiling surfaces maintained at same temperature) for sedentary subjects.

Since comfort is a subjective concept, it is natural to select a subjective scale that serves to evaluate feelings of thermal comfort. Evaluation of thermal comfort was accomplished in this study by a subject's indication of his thermal sensation to his environment on the ballot shown in Figure 1. Thermal comfort (to be interpreted as thermal neutrality for this analysis) was then defined as a response to environmental conditions which resulted in an average vote between 3.5 and 4.5 on this ballot. This ballot has been used in previous studies (58) (63).

A linear statistical model was selected to describe the "thermal sensation" responses of the subjects to the environments of combinations of MRT and air temperature. The model was (13):

$$\hat{Y} = a + b_1 (t_a - \bar{t}_a) + b_2 (t_{mrt} - \bar{t}_{mrt})$$

where:

$\hat{Y}$ = estimated "thermal sensation" vote

a = mean "thermal sensation" vote

Subject

Name_________________________No.______

Circle the number that describes how you feel:

1. Cold

2. Cool

3. Slightly Cool

4. Neutral

5. Slightly Warm

6. Warm

7. Hot

____

____

Figure 1. The ballot used to evaluate the "thermal sensation" response of the subjects.

b_1, b_2 = partial regression coefficients

t_{mrt} = the independent variable representing mean radiant temperature as measured by a Honeywell radiometer ($\bar{t}_{mrt}$ = mean t_{mrt})

t_a = the independent variable representing dry bulb air temperature ($\bar{t}_a$ = mean t_a)

Snedecors - F test (27) was used to test for "lack of fit" of the data to the linear model with a 5% level of significance. If "lack of fit" proved to be significant then a curvilinear model would be selected by adding terms containing the products of the independent variables and/or higher powers of the independent variables.

A series of eight combinations of MRT and air temperature was selected that was expected to elicit average votes of about 3 to 5 on the "thermal sensation" ballot. Previous work was consulted to make this selection. The experimental points are indicated in Figure 7, which also shows the results. It was decided to expose twenty college-age subjects (10 male and 10 female) to each experimental point, the minimum number that was felt necessary for a meaningful estimate of the response of a larger number of subjects (based upon the results from past analysis) (58) (60) (63). Photographs of the subjects in the test chamber are presented in Figures 2 and 3. Lines representing conditions of equal heat loss for sedentary subjects in environments of various combinations of MRT and air temperature developed by previous investigators were used in selecting the experimental points for the present study. These are indicated in Figure 4. The lines are drawn through a point of equal MRT

Figure 2. A view of the test chamber showing the typical placement of the subjects for the sedentary tests.

Figure 3. A typical view showing the placement of the subjects and the radiometer in the sedentary tests.

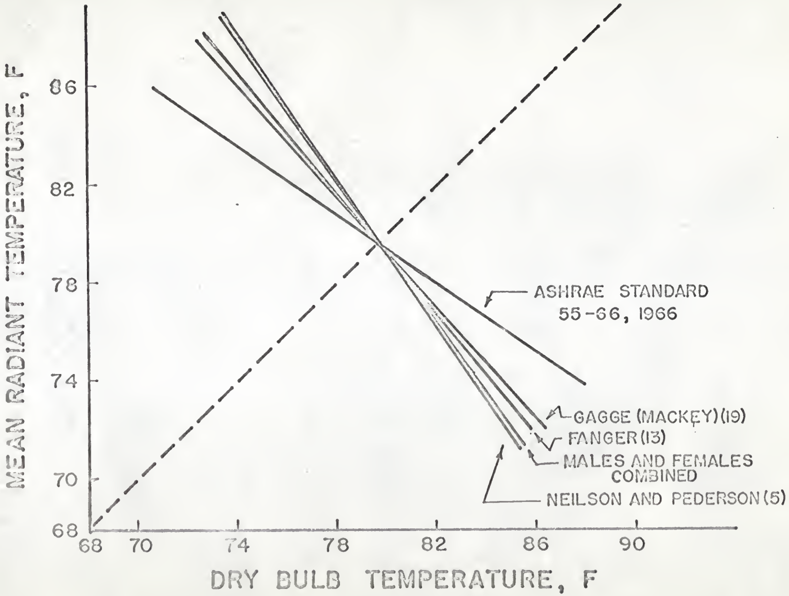

Figure 4. MRT vs. dry bulb temperature relationship for a neutral "thermal sensation" (vote = 4.0) of males and females combined. Also shown are "thermally neutral" lines predicted from the results of previous investigators.

and air temperature which represents an average "thermal sensation" vote of 4.0 predicted from previous studies (63).

The partial pressure of water vapor in the air was maintained at 0.435 inches of mercury (45% RH at 78F) throughout all the tests to keep the diffusion heat loss relatively constant since the mass transfer of moisture from the subjects body to the air is dependent upon the vapor pressure gradient (6) (12) from the skin to the air. Evaporative heat loss of the magntude expected is relatively independent of vapor pressures normally found in comfortable environments (46). The mean air velocity in the occupied area of the test chamber was approximately 25-30 fpm, the illumination intensity at the desk top level was 133 foot-candles and the noise level was 69 decibels on the all band-pass scale of an octave band sound analyzer. These values were held constant throughout the tests. The MRT was measured in all tests by a Honeywell radiometer (67).

The environmental test points selected were felt to be representative of practical extremes found in most comfortable office environments and/or shop environments where relative air velocities are low.

Facilities

This research project was carried out at the Institute of Environmental Research, Department of Mechanical Engineering, Kansas State University, Manhattan, Kansas. This facility was financed jointly from funds provided by the Kansas Legislature and a matching grant from the Health Research Facilities Branch

of the National Institute of Health, Department of Health, Education and Welfare.

The Institute houses the KSU-ASHRAE Environmental Test Chamber which was a gift from the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE). The facility was originally located at the ASHRAE Laboratory at Cleveland, Ohio and was moved to Kansas State University and placed in operation in November, 1963. The tests were performed in this environmental chamber which is 12 feet wide, 24 feet long, and has a ceiling height which is adjustable from 8 feet to 11 feet. During these tests, the height was 8 feet. A floor plan of the chamber and adjoining facilities is shown in Figure 5, and a view of the control panel is shown in Figure 6.

All interior surfaces of the test chamber are aluminum to which copper tubes are attached on the back. These copper tubes carry heated and/or chilled water to control the surface temperatures. The liquid circuits are arranged to provide four independent circuits: one for the floor, one for the ceiling, and two for the walls. This provided flexibility in maintaining different surface temperatures to simulate various conditions of symmetric and asymmetric radiant temperature distribution. Surface temperatures are variable between 40 and 150F.

The system was designed so that air temperatures from 40 to 150F and relative humidities between 10% and 95% could be maintained through the system consisting of a capillary washer, a sorbent dehumidifier, separate heating and cooling coils, fans,

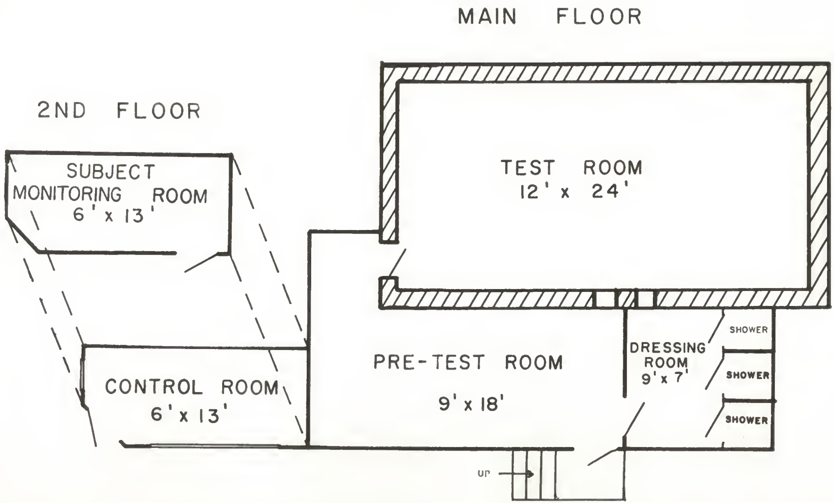

Figure 5. Floor plan of the KSU-ASHRAE Environmental Laboratory facility.

Figure 6. The control room of the KSU-ASHRAE Environmental Laboratory facility.

and ducting. Conditioned air enters through perforated inlet strips located between the ceiling panels and exits through a continuous slot at the floor around the perimeter of the room. It is possible to provide up to 50 air changes per hour.

A 15 hp refrigerator compressor supplies a 300 gallon insulated chilled-liquid supply tank. The chilled liquid is circulated through the tank and heat exchanger by a pump which also provides adequate mixing in the tank. The temperature of the liquid in the tank is controlled by a pneumatic thermostat. A 220 gallon hot-liquid storage tank is provided and maintained with steam supplied by the University boilers. Utilizing a system of pneumatically controlled mixing valves and thermocouples, liquid with the desired temperature can be circulated through the panels of the four independent circuits.

The entire system is remotely and automatically controlled from the control room (Figures 5 and 6) adjacent to the pre-test room. Electronic and pneumatic control equipment is used to maintain the predetermined conditions. The dry and wet bulb temperatures in the test room are measured by a motorized psychrometer. An indicating potentiometer and a multipoint recorder are provided to measure wall surface temperatures and air temperatures. Two graphic control panels are provided, one for the air circuit and one for the liquid circuits. Lights indicate those parts of the system which are in operation. Air or liquid temperatures at various locations in the system can be monitored. A physiological monitoring room is located above the control room.

Instrumentation for measuring skin temperature, rectal temperature, and heart rate is available. Operant conditioning and programming equipment is also located in this room.

A more detailed description of the orginal facility in Cleveland including construction, design, piping circuits, electronic controls, etc., is available from Tasker, et al. (68). A description of the present facility was included in the recent paper by Nevins, et al. (63).

The Honeywell two-sphere radiometer (67) used to evaluate MRT for each test has one polished gold-plated sphere and one black-painted sphere, each containing heating coils, and each being thermostatically controlled. These spheres then have different emissivities and absorptivities for radiant heat transfer. The radiometer eleminates the effect of convection to the environment by maintaining the two spheres at a common temperature above the air temperature. Therefore, the additional power required of one sphere over the other to maintain the set-point temperature is a function of the MRT (since conduction and convection losses are the same for both spheres) which can then be evaluated with the aid of operating curves accompanying the radiometer. The radiometer is non-directional and the average error has been measured as less than 0.4F (49). For the sedentary tests, the radiometer was placed in a position in the chamber similar to that of the subjects (Figure 3 and Appendix A) with the spheres two feet from the floor.

Procedure

All tests were conducted in the afternoon or evening during the period February to July, 1967, inclusive. The subjects were randomly assigned to a testing session, and no subject was used more than once. This resulted in a completely randomized design. It was felt that subjects naive in the practice of voting on a "thermal sensation" ballot and interpreting the terms on the ballots would more likely be a representative, normal population than subjects specially instructed. All the subjects employed for the environmental tests were given an examination by a physician at the Kansas State University Health Service. A registered nurse and an assistant served as monitors for each test. They recorded data taken in both the pre-test room and the test chamber.

As the subjects arrived for a testing session, they were given cotton twill uniforms to wear which had an insulation value of approximately 0.60 clo (58). The underclothing consisted of brassieres and underpants for the women and shorts (no undershirts) for the men. They wore cotton sweat socks but no shoes. Figure 2 shows the subjects dressed in this clothing. The height, clothed weight, and oral temperature were taken for each subject in the pre-test room which was maintained at approximately 74F dry bulb air temperature and 50% relative humidity. The summary of physical data for the subjects used in the sedentary tests are shown in Table 1. Additional information was obtained from the subjects which might aid in explaining unusual varia-

tions in the data, e.g. amount of alcohol consumed in the past 24 hours, amount of sleep and work in the past 24 hours, etc. The test room monitors also indicated on the record sheets any lack of cooperation on the part of any test subject which might affect results. The subjects remained seated for one-half hour in the pre-test room before entering the test chamber immediately adjacent.

Table 1

Physical Data for the Subjects Used in the Sedentary Tests

Sex	No. of Subjects	Age (yr)	Height (in)	Weight (lb) (Nude)	Surface Area (ft^2) (Nude)
Males	80	20.2* ± 3.1**	69.0 ± 2.4	162.0 ± 18.0	20.24 ± 1.29
Females	80	19.8 ± 2.4	64.4 ± 2.2	132.1 ± 16.5	17.61 ± 1.20

* Mean
** Standard deviation

After an oral indoctrination explaining the purpose and procedure of the test (see Appendix B for this oral indoctrination), the subjects entered the test chamber. The men and women were randomly assigned to their respective positions (Appendix A). The subjects were each provided with a classroom desk-chair and two 1-foot square, two-inch thick foam rubber pads; one to sit on and the other to place their feet on to reduce conducted heat to

the floor (Figure 2). There were no indications of foot discomfort.

The exposure time was three hours for all tests. The subjects were allowed to study, read, or engage in limited conversation while in the test chamber. No subject was allowed to leave until the full three hours were completed. The subjects were allowed to drink tap water ad lib, and the amount consumed was recorded for each subject. The subjects were allowed to stand and stretch for one minute in the sedentary tests after $1\frac{1}{2}$ hours of exposure (after the fourth vote was taken). No one was allowed to sleep. The "thermal sensation" ballot was handed individually to the subjects immediately upon entering the test chamber and a new ballot was presented at each succeeding half hour resulting in a total of seven votes for each individual during each test. The ballots were collected immediately after each voting period and the results recorded.

Following the last vote at the end of the third hour, the subjects again entered the pre-test room. Their final clothed weight was taken after which they were paid and allowed to leave.

RESULTS

The central purpose of this study was to determine the relative importance of mean radiant temperature and air temperature in and near the zone of "thermal neutrality" for persons in simulated practical activities and environments. This was done with air velocities in the region of 25-30 ft/min and water vapor pressure of 0.435 inches Hg (45% RH at 78F). Under these conditions the results showed that for sedentary males surrounded by a uniform MRT, a 1F increase in air temperature is offset by a 1.51F decrease in MRT or vice-versa. For females, a 1.37F decrease in MRT is necessary, and for males and females combined, a 1.43F decrease in MRT is required. This is to say that air temperature is a more important variable than mean radiant temperature even with low air velocities. This result may be also expressed as the ratio of h_C/h_R, where:

h_C = convection heat transfer coefficient, $B/hr/F/ft^2$ nude area

h_R = radiation heat transfer coefficient, $B/hr/F/ft^2$ nude area

Table 2 shows the measured values of the ratios of h_C/h_R for males, females, and males and females combined. Table 2 also shows comparisons with values calculated from Fanger's Basic Comfort Equation (12). Sample computations are shown in Appendix C.

Table 2

Magnitudes and Ratios of the Radiation (h_R) and Convection (h_C) Heat Transfer Coefficients that are Computed and/or Measured for Sedentary Human Subjects

Sedentary Subjects	COMPUTED, FANGER'S COMFORT EQUATION (12)			MEASURED, THERMAL SENSATIONS
	h_C*	h_R*	h_C/h_R	h_C/h_R
Males, Females Combined	0.92	0.75	1.23	1.43
Males	0.92	0.75	1.23	1.51
Females	0.92	0.75	1.23	1.37

Parameters used in computations:

Partial Pressure of Water Vapor in the Air = 0.435 in. Hg
Clothes Insulation = 0.59 clo
Relative Velocity: Sedentary - 25-30 fpm
Metabolic Rate (Btu/hr): Sedentary - 345 Btu/hr

* dimensions are Btu/hr/F/ft^2 nude area

Lines representing "thermal sensation" votes and the thermally neutral zone are presented in Figure 7. These results are developed by multiple regression analysis of the "thermal sensation" responses of the sedentary subjects for males and females combined. The analyses were performed on the average vote on the "thermal sensation" ballot taken during the last

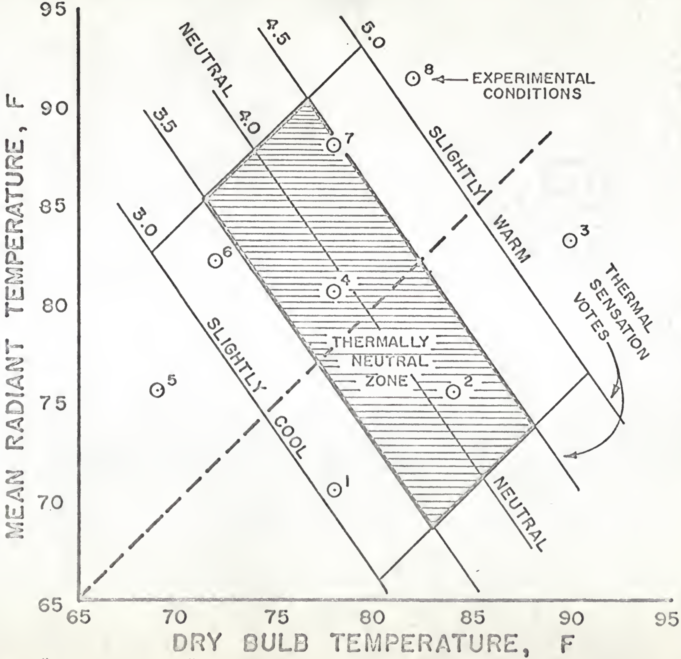

Figure 7. The "thermally neutral" zone for sedentary subjects. The experimental points investigated are indicated in the figure. Also shown are lines representing "thermal sensation" votes of 3.0 to 5.0.

hour of exposure. This average of the last three votes was felt to result in a more stable and representative response than the vote at one time. Previous studies indicated, that equilibrium is reached before the third hour (40) (59). (Figure 9 shows the trend of the mean vote with time during these tests.) To show the relative responses of males and females, lines representing average "thermal sensation" votes of 4.0 for males, females, and combined responses of males and females are shown in Figure 8.

The regression equations for the response to environments of symmetric MRT of sedentary males, females, and males and females combined are:

$$Y_m = \underset{(1.164)^*}{-9.126} + \underset{(0.012)}{0.099}\, t_a + \underset{(0.012)}{0.066}\, t_{mrt} \quad (1)$$

$R^2 = 0.629$ $\quad s_{Y \cdot t_a,\ t_{mrt}} = 0.651$ $\quad N = 80$

$$Y_f = \underset{(1.360)}{-12.845} + \underset{(0.014)}{0.122}\, t_a + \underset{(0.014)}{0.089}\, t_{mrt} \quad (2)$$

$R^2 = 0.668$ $\quad s_{Y \cdot t_a,\ t_{mrt}} = 0.761$ $\quad N = 80$

$$Y_c = \underset{(0.899)}{-10.986} + \underset{(0.009)}{0.111}\, t_a + \underset{(0.009}{0.077}\, t_{mrt} \quad (3)$$

$R^2 = 0.643$ $\quad s_{Y \cdot t_a,\ t_{mrt}} = 0.712$ $\quad N = 160$

where:

Y_m = estimated "thermal sensation" vote of college-age males for a given combination of air temperature and MRT

Y_f = estimated "thermal sensation" vote of college-age females for a given combination of air temperature and MRT

*number in parentheses represents the standard deviation of the variate immediately above them

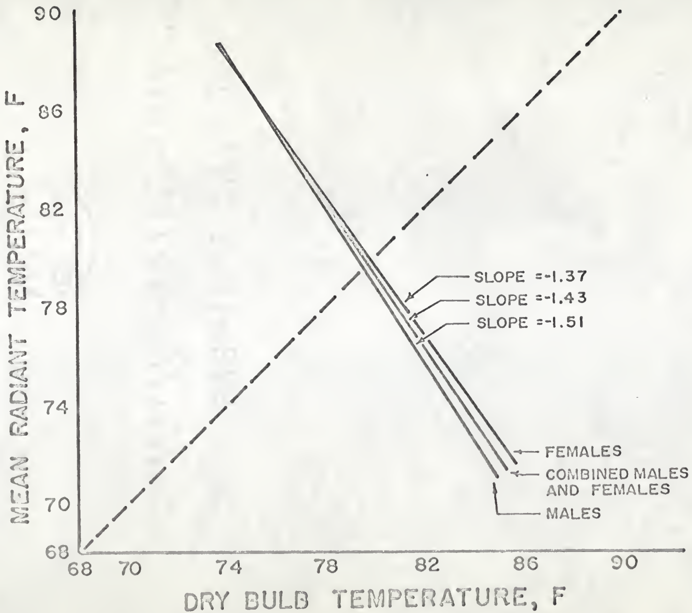

Figure 8. Lines representing a "thermal sensation" vote of 4.0 for sedentary males, females, and combined groups of males and females.

Y_c = estimated "thermal sensation" vote of college-age males and females combined for given combinations of air temperature and MRT

t_a = the independent variable representing dry bulb air temperature (F)

t_{mrt} = the independent variable representing MRT (measured with the Honeywell radiometer), (F)

R^2 = square of the multiple linear correlation coefficient

$S_{Y \cdot t_a, t_{mrt}}$ = estimated standard deviation of the "thermal sensation" votes for a given value of the independent variables

N = number of subjects

Snedecors -F test (27) was used to test for "lack of fit" on the results and it was determined (with a 5% level of significance) that a mathematical model of higher degree would not explain the results significantly better than the linear models presented. (Appendix D)

An analysis of variance revealed that the subjects' responses were independent of their position in the room for all tests in this study and is shown in Appendix E.

DISCUSSION

The energy balance for a person which demonstrates the roles of the physical and physiological mechanisms involved in production, storage, and transfer of energy of the body is represented by the following equation:

$$M = \pm S + E \pm R \pm C_v \pm C_d \pm W \qquad (4)$$

where:

M = metabolic rate, internal energy production

S = storage rate, change in internal energy

E = rate of evaporative heat loss, includes sensible and insensible perspiration*

R = rate of radiative heat loss or gain

C_v = rate of convective heat loss or gain, includes dry respiration loss and heat loss from outer surfaces of the body

C_d = rate of conductive heat loss or gain

W = rate of external mechanical work

All the terms are considered to be per unit nude surface area of the body.**

For a sedentary person in an environment that lies within the "thermally neutral" zone (Figure 7), the rate of storage (S) is essentially zero after two hours of exposure since the

*insensible perspiration: evaporation of water from respiratory tract plus the diffusion through the skin, sensible perspiration: secretion of sweat glands

**nude body surface area computed by DuBois equation

person is at equilibrium with his environment. The conducted heat transfer (C_d) is negligible since the surfaces that the body is in contact with typically have low conductance. The external work (W) is zero. The metabolic rate (M) is relatively constant (59). The evaporative heat loss (E) is a positive constant (12). The simplified equation for a sedentary individual becomes:

$$M - E = \pm C_v \pm R \tag{5}$$

The radiation (R) may be represented by:

$$R = f_r e \sigma \left[(t_s + 460)^4 - (t_{mrt} + 460)^4 \right] \tag{6}$$

where:

f_r = effective radiation area factor, as a fraction of DuBois area, determined by subject's body posture and clothing ensemble

e = emissivity of the subject's skin and clothing surface exposed to the environment

σ = Stefan-Boltzman radiation constant ($B/hr/ft^2/R^4$)

t_s = the mean surface temperature of the subject (F)

t_{mrt} = the mean radiant temperature of the environment (F)

For the temperature differences normally occurring in the "thermally neutral" zone, this equation is nearly linear* (65) and can be reduced to:

$$R = h_R \, (t_s - t_{mrt}) \tag{7}$$

where:

h_R = approximated as constant for a given posture and type of clothing ($B/hr/ft^2/F$)

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*see Appendix F

t_s = mean surface temperature of the subject (F)

t_{mrt} = mean radiant temperature of environment (F).

The convection heat transfer is evaluated by (12):

$$C_v = f_{cl}\ h'_c\ (t_s - t_a) \text{ for relative air velocity } 20 \text{ fpm} \tag{8}$$

or:

$$C_v = f_{cl}\ h_c\ (t_s - t_a) \text{ for relative air velocity } 20 \text{ fpm} \tag{8a}$$

where:

h'_c = free convection heat transfer coefficient; a function of $(t_s - t_a)^{0.25}$ $(B/hr/ft^2/F)$

h_c = forced convection heat transfer coefficient $(B/hr/ft^2/F)$; a function of $\sqrt{V}$, where V is relative velocity (fpm)

f_{cl} = effective convection area factor as a fraction of DuBois area due to the clothing

t_a = air temperature (F).

For the "thermally neutral" zone and given air velocity this equation is also approximately linear and can be reduced to:

$$C_v = h_C\ (t_s - t_a) \tag{9}$$

where h_C can be approximated as a constant for a particular combination of clothing ensemble and subject's body posture. The energy balance on the person after the preceeding assumptions and approximations have been applied appears as:

$$R + C_v = h_R\ (t_s - t_{mrt}) + h_C\ (t_s - t_a) \tag{10}$$

Further simplification of equation 10 yields:

$$h_R\ t_{mrt} + h_C\ t_a = t_s\ (h_R + h_C) - (R \quad C_v) \tag{11}$$

The right side of equation 11 is a constant in the "thermally neutral" zone since all the radiation and convection heat loss

is conducted through the skin requiring t_s to remain constant (12). Differentiation of equation 11 and rearrangement yields:

$$dt_{mrt}/dt_a = -h_C/h_R \tag{12}$$

where dt_{mrt}/dt_a represents the slope of the function given in equation 12 on the air temperature - MRT plane. Since the equation is linear, the slope can be represented by:

$$dt_{mrt}/dt_a = \Delta t_{mrt}/\Delta t_a \tag{13}$$

The linear form of equation 11 is manifested in the regression equations for "thermal sensation" as a function of MRT and air temperature (equations 1, 2, and 3). It is assumed that a person's thermal sensations are governed by the same physical laws that govern heat loss from the body. Therefore, the relative effects of convection and radiation heat transfer for a person who is "thermally neutral" can be evaluated by the slope of the line representing a "thermal sensation" vote of 4.0 in the MRT - air temperature plane. The slope is -1.43 for the response of sedentary males and females combined. This indicates that air temperature is 1.43 times as "important" as MRT for constant "thermal sensation". To illustrate: if a person in a given environment was comfortable ("thermal sensation" vote = 4) and the air temperature was then reduced 1.0F, the MRT would have to be elevated 1.43F to give the person the same thermal sensation that he had before the change.

The form of equation 12 was previously suggested by Gagge (17), and the constant represented by the right side of the equation was defined as the "operative temperature".

Using Fanger's Comfort Equation (12), the computed ratio of h_C/h_R shows good agreement with the ratio evaluated by the subject's "thermal sensation" responses (Table 2). Equation 11 is a linear approximation of Fanger's Comfort Equation for the conditions of these tests. Values of h_C and h_R can be obtained from Fanger's equation by first computing the mean skin temperature for the predicted metabolic rate and then computing the mean outer surface temperature of the clothed subject for the required radiation and convection heat loss that is conducted through the average resistance of the clothing:

$$R \quad C_v = \frac{\bar{t}_s - t_s}{(0.88) I_{cl}} \tag{14}$$

where:

$\bar{t}_s$ = mean skin temperature (F)

t_s = mean outer surface temperature of the subject (clothing and exposed skin) (F)

I_{cl} = thermal resistance of the clothes (clo).

The value of $R \quad C_v$ can be determined experimentally since the heat loss equation shows:

$$R + C_v = M - E$$

and E can be determined by a mass balance on the subject. In the absence of weight loss data, an alternate method is to find a value of $R \quad C_v$ that satisfies both Fanger's Comfort Equation and equation 14. This represents a trial and error process, but will give a good estimate of $R + C_v$, E, and t_s.

To determine actual values of h_C and h_R that occured

in these tests to compare with values of h_C and h_R that were computed from Fanger's Comfort Equation (Table 2), the computed value of R C_v, which is 12.30 B/hr/ft^2 for males and females combined (Appendix C), and the values of $(t_s - t_{mrt})$ and $(t_s - t_a)$, which is 7.4F for $t_{mrt} = t_a$ (appendix C), can be inserted into equation 10 to give:

$$12.30 = h_R\ (7.4) + h_C\ (7.4)$$

Then with the observed value of $h_C/h_R = 1.43$ for males and females combined, it can be determined that $h_C = 0.98$ and $h_R = 0.68$. This can be compared to the values computed (Table 2) for h_C and h_R which are 0.92 and 0.75 respectively. These values suggest that better agreement with Fanger (12) could be accomplished by increasing the convection coefficient in the expression that he adopted. It can be shown that Fanger's expression for h_C would need to be changed from (Appendix C):

$$h_C = (0.152)\ f_{cl} \sqrt{V}$$

to:

$$h_C = (0.163)\ f_{cl} \sqrt{V} \tag{15}$$

If Fanger were to adapt equation 15 to his Comfort Equation, the Comfort Equation predictions would more closely correspond to the results of this study. This suggestion needs to be tempered with knowledge of the fact that only one air velocity was present in all tests of the present study and points to the need for further testing with different air velocities for verification. In the absence of meaningful evaporative heat (sweat loss) data, the validity of equation 15 rests upon the validity of Fanger's

(12) evaporative heat loss analysis for his Basic Comfort Equation and the accuracy of the many subjects' responses analyzed in the present study. The analysis in Appendix C shows that for the metabolic rate of males and females combined, the evaporative heat loss represents 32% of the metabolic heat production. This value is above the value of 25% which is sometimes cited and below the value of 40% which is indicated by recent studies (59). The accurate assessment of evaporative heat loss also is an area of research which needs strict attention in the future in order to develop more exact expressions for the values of the convection and radiation heat transfer coefficients.

The analysis for the regression equations resulting from these tests reveals the high variablility inherent in any study dealing with physiological responses. This variation is due not only to true differences of feelings of thermal sensation, but from variations in physiological parameters both within and between individuals (such as basal metabolic rate, heart rate, and other normal body functions). Differences between the sexes in response to the thermal environment are usually notable (32) (58). However, the females on the average responded similarly to the males for the different environments of the sedentary tests (Figure 8). A recent study from this laboratory (57) has shown that "thermal sensations" and "comfort sensations" for males and females combined are relatively unaffected by asymmetric temperature distributions of up to 12F; therefore the thermally neutral zone developed in this study for sedentary

subjects in an environment with a symmetric MRT can be expanded to include environments of asymmetric MRT where the subject has a shape factor of 0.2 to a surface at one temperature and a shape factor of 0.8 to the balance of the surfaces at another temperature of up to 12F difference. The results of another recent study (56) indicates that the relative effects of convection and radiation remain essentially unchanged at a higher activity level when that activity level is defined by alternating periods of walking over a set of two nine-inch steps and standing at rest. This effect at a higher activity level is due in large part to the simultaneous increase in h_C due to increased air velocity and h_R due to increased effective radiation area over the respective values for a seated individual. However, the thermally neutral zone is naturally shifted to lower temperatures and is wider due to the decrease of sensitivity to the environment of active people. For combined males and females, the width of the "thermally neutral" zones are:

1. Sedentary, "thermally neutral" zone is 5.3F wide
2. Activity (metabolic rate = 829 B/hr for males, metabolic rate = 654 B/hr for females), "thermally neutral" zone is 12.1F wide

The activity results are from previous investigations (56) (58).

The initial reaction (first vote) of the subjects to the environments of the sedentary MRT tests was such that the relative effect of convection and radiation heat transfer (h_C/h_R) was only 1.17. This indicates a nearly equal affect of convection and radiation on the "thermal sensation" vote. This is

approximately 20% less than the relative effects found for the response of the last hour of a three hour exposure. The reasons for the differences between initial thermal sensations and thermal sensations after equilibrium was attained are not fully understood. The results of this test, however, were based on equilibrium conditions for the subjects which is obtained well before the third hour but probably requires at least 20-40 minutes (40). Equilibrium was indicated by the relatively small changes in average votes after the first 30 minutes of exposure as shown in Figure 9.

The effect of relative humidity or type of clothing on the relative effects of convection and radiation for a sedentary person in the "thermally neutral" zone should be small. Nevins, et al. (53) showed that relative humidity in the range of 20% to 65% had little effect on the comfort response in the zone of "thermal neutrality." The type of clothing would be expected to elicit differences in response generally only in extreme cases of tight or loose weaves that restrict or promote excessive convection current under the clothing, thereby altering the convection and evaporative effects from the experimental conditions of this study. An adjustment for clothing ensembles of different insulation values may be made by a translation of the line representing thermal neutrality

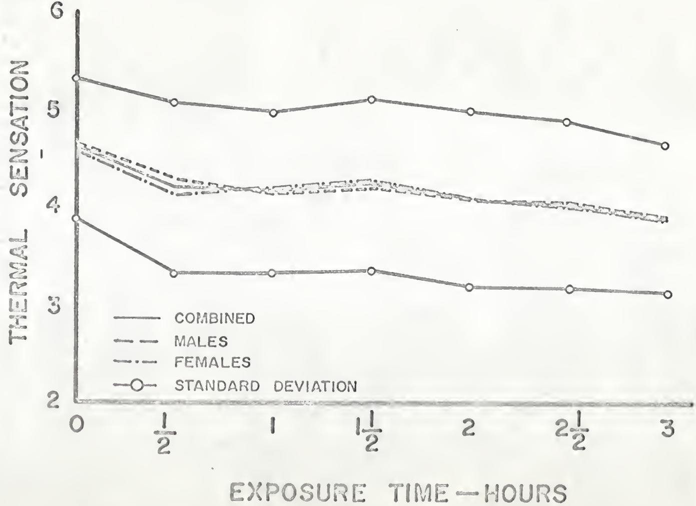

Figure 9. The trend of mean "thermal sensation" votes with time of exposure.

for this study to the equivalent temperature* required for thermal neutrality of the given clothing insulation. The effect of increasing relative air velocity will obviously increase the effect of the convection heat transfer (as well as the evaporative heat loss). Adjustments for increased air velocity, clothing, etc., can be made by the application of Fanger's (12) Thermal Comfort Equation or the methods of Mackey (53) as developed by Gagge (17) which show generally good agreement with the results of this study.

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*The equivalent temperature for an environment of unequal MRT and air temperature is that combination of equal MRT and air temperature that evoke similar "thermal sensations". Equivalent temperature lines are parallel to "thermal sensation" vote lines in the air temperature-MRT plane. The equivalent temperature is defined for constant air velocity and constant partial pressure of water vapor in the air.

SUMMARY AND CONCLUSIONS

The following shows the relative influence of convection and radiation heat transfer, determined by the ratio of the convection heat transfer coefficient (h_C) to the radiation heat transfer coefficient (h_R), for sedentary people wearing clothes with an insulation value of 0.59 clo in equilibrium with environments that have a partial pressure of water vapor of 0.435 in Hg and a relative air velocity of 25-30 fpm:

1. Males (metabolic rate = 389 Btuh), h_C/h_R = 1.51
2. Females (metabolic rate = 301 Btuh), h_C/h_R = 1.37
3. Males and females combined (metabolic rate = 345 Btuh), h_C/h_R = 1.43, recommended value 1.4

A zone of thermal neutrality* has been developed for sedentary groups of males and females combined as shown in Figure 7 for environments of symmetric MRT and for asymmetric MRT for differences up to 12F.

The results show generally good agreement with Fanger's (12) Comfort Equation in the environments investigated, indicating the validity of Fanger's Equation for predicting thermally neutral environments. However, an expression is suggested for the convection heat transfer coefficient for sedentary subjects in the thermally neutral zone as an adjustment in the Comfort

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*combinations of MRT and air temperature such that subjects on the average wish to be neither cooler nor warmer

Equation:

$$h_c = (0.163)\, f_{cl} \sqrt{V}$$

where:

h_c = convection heat transfer coefficient ($B/hr/ft^2$ nude area)

f_{cl} = effective convective area factor as a fraction of nude area due to clothing

V = relative air velocity (fpm)

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A P P E N D I C E S

APPENDIX A

Figure A-1 shows the subject and equipment arrangements in the test chamber for the sedentary comfort tests.

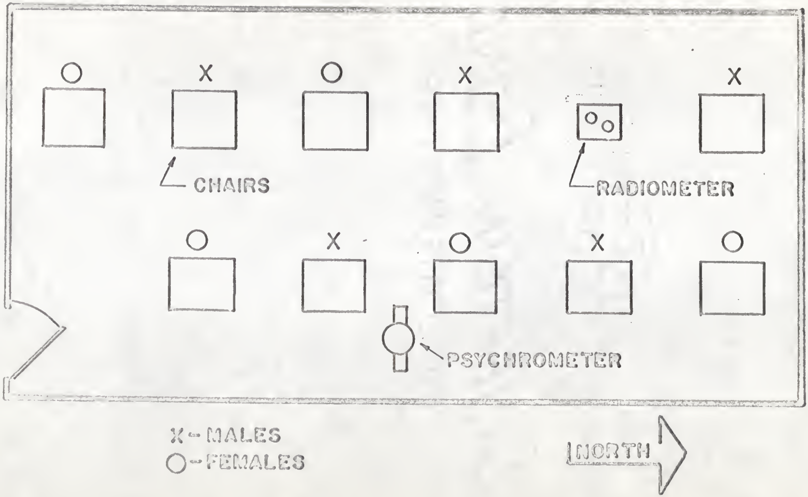

Figure A-1. The arrangement of the environmental test chamber for the sedentary tests. The chamber floor is 12 feet by 24 feet and the ceiling height is 8 feet.

APPENDIX B

INDOCTRINATION INFORMATION: Read to Subjects Before Each Test

The purpose of this test is to determine the effect of temperature on how you feel. As soon as preparations are completed in the pre-test room, we will take you into the test room next door. Select one of the chairs and be seated. Do not move the chairs from their original locations.

During the test, you may read, study, or engage in quiet conversation. You may smoke but keep it to a minimum. At various intervals, you will be asked to vote on your feeling of thermal sensation (show sample ballot). You will record your votes on the two separate ballots provided. Do not discuss your votes with one another. Remember, we want to know the way you feel at the time the ballot is handed to you! The thermal sensation ballot has seven conditions from which you can select the one which best describes your feeling at that time. Condition No. 4 is thermally neutral which should be selected when you feel the test room should be neither warmer nor cooler.

Water will be provided and since the amount you drink will be measured, you should drink only out of the cup assigned to you, but you may have all the water you wish.

When the test is finished go to your respective dressing rooms and get dressed. The women should put their shirts, trousers, and socks in one pile in the dressing room. The men should

place their uniforms and socks on the table by the pre-test room door. Do not leave uniforms in the men's restroom.

All persons participating in these tests will sign a receipt for your pay, $5.00, which will be given you at the end of the test.

Are there any questions?

APPENDIX C

The following represents sample computations of h_C and h_R from Fanger's Basic Comfort Equation (12) by trial and error solution for sedentary subjects experiencing "thermal neutrality".

The radiation heat transfer (R, $B/hr/ft^2$ nude area) is given by:

$$R = \frac{f_r f_{cl} e \sigma}{10^{-8}} \left[((t_s + 460)/100)^4 - ((t_{mrt} + 460)/100)^4\right] \quad (C-1)$$

where:

σ = Stefan - Boltzman constant ($B/hr/R^4/ft^2$)

e = emissivity of the subjects' surface area

f_r = effective radiation area factor as a fraction of nude area

f_{cl} = effective convective area factor as a fraction of nude area

t_{mrt} = mean radiant temperature (F)

t_s = mean temperature of the subject's surface area (F)

I_{cl} = the insulation value of the standard clothing (clo)

The convection heat transfer (C_v, $B/hr/ft^2$ nude area) is calculated by:

$$C_v = f_{cl}\, h_c\, (t_s - t_a) \quad (C-2)$$

where:

h_c = convection heat transfer coefficient ($B/hr/F/ft^2$)

t_a = dry bulb air temperature (F)

The subjects' mean surface temperatures, t_s (F), and mean

skin temperature $\bar{t}_s$ (F), which are obtained by regression analysis (12) (59), are related in the following manner (46) for the dry heat ($C_v + R$) that is conducted through the average resistance of the clothing:

$$C_v + R = \frac{\bar{t}_s - t_s}{I_{cl}\ (0.88)} \tag{C-3}$$

or alternatively:

$$t_s = \bar{t}_s - (C_v + R) \cdot I_{cl} \cdot (0.88) \tag{C-4}$$

For a seated sedentary subject (males, females combined) with a relative air velocity (V,fpm) of 30 fpm, the following represents values of the factors used in equations C-1, C-2, and C-4 for heat transfer calculations:

$$h_c = (0.152)\sqrt{V} = 0.83 \text{ B/hr/F/ft}^2 \text{ nude area}$$

$$\sigma = 0.1713 \cdot 10^{-8} \text{ B/hr/R}^4\text{/ft}^2$$

$$e = 0.95$$

$$f_r = 0.65$$

$$f_{cl} = 1.1$$

$$\bar{t}_s = 93.48\text{F}$$

$$I_{cl} = 0.60$$

$$t_s = 93.48 - (C_v + R) \cdot (0.52)$$

The regression equation 3 predicts that males and females combined will feel "thermally neutral" for $t_{mrt} = t_a$ at 79.7F. Assume that t_s = 87.1F; then:

$$R = (0.1713) \cdot (0.95) \cdot (0.65) \cdot (1.1)\ \left[(5.471)^4 - (5.397)^4\right] = (0.1164) \cdot (895.92 - 848.42) = 5.53 \text{ B/hr/ft}^2 \text{ nude area}$$

and:

$$C_v = (1.1) \cdot (0.83) \cdot (87.1 - 79.7) = (0.92) \cdot (7.4) = 6.77$$
$B/hr/ft^2$ nude area

Now check assumed value of t_s using computed values of R and C_v in equation C-4:

$$t_s = 93.48 - (6.77 + 5.53) \cdot (0.52) = 87.09 \qquad \text{Q.E.D.}$$

Define for environments where thermal sensation rate = 4.0:

$$h_C = C_v/(t_s - t_a) \text{ and } h_R = R/(t_s - t_{mrt})$$

Then:

$$h_C = 6.77/(7.4) = 0.92$$

$$h_R = 5.53/7.4 = 0.75$$

APPENDIX D

Tables D-1, D-2, and D-3 show the statistical analyses testing "lack of fit" of the linear mathematical model assumed for the effect of air temperature and MRT on thermal sensations. A 5% level of significance was assumed; ns indicates non-significance.

Table D-1

Analysis Testing for "Lack of Fit" of Linear Model to "Thermal Sensation" Responses of Males and Females Combined

Source of Variation	Degrees of Freedom	Corrected Sum of Squares	Mean Square	F
Error ($S_{Y \cdot t_{mrt}, t_a}$)	157	79.50	0.71	
Difference	5	4.67	0.93	$\frac{0.93}{0.49} = 1.90^{ns}$
Error (random)	152	44.82	0.49	

Table D-2

Analysis Testing for "Lack of Fit" of Linear Model to "Thermal Sensation" Responses of Males

Source of Variation	Degrees of Freedom	Corrected Sum of Squares	Mean Square	F
Error ($S_{Y \cdot t_{mrt}, t_a}$)	77	32.67	0.65	
Difference	5	1.94	0.39	$\frac{0.39}{0.43} = 0.91^{ns}$
Error (Random)	33	30.73	0.43	

Table D-3

Analysis Testing for "Lack of Fit" of Linear Model to "Thermal Sensation" Responses of Females

Source of Variation	Degrees of Freedom	Corrected Sum of Squares	Mean Square	F
Error ($S_{Y \cdot t_{mrt}, t_a}$)	77	44.64	0.76	
Difference	5	3.92	0.78	$\frac{0.78}{0.56} = 1.39^{ns}$
Error (random)	72	40.72	0.56	

APPENDIX E

Table E-1 shows the statistical analysis performed to determine if "thermal sensation" responses were independent of position in the test chamber. The analysis is performed for three environmental conditions with two replications for each condition where each replication contains five males and five females. A 5% level of significance was assumed; ns indicates non-significance.

Table E-1

Analysis of Variance to Determine Independence of Thermal Sensation From Position

Source of Variation	Degrees of Freedom	Corrected Sum of Square	Mean Square	F
Conditions	2	108.81	54.41	
Sex	1	2.14	2.14	
Position within Sex	8	5.22	0.65	$\frac{0.65}{0.48} = 1.37^{ns}$
Condition, Sex Interaction	2	5.15	2.58	
Condition, Position within sex interaction	16	10.62	0.66	
Error	30	14.33	0.48	
Total	59			

APPENDIX F

Radiation heat transfer calculations can be greatly simplified when a linear approximation can be adapted without sacrificing a significant amount of accuracy. Figure F-1 shows that the substitution of a linear temperature difference $(t_h - t_c)$ for the difference of absolute temperatures to the fourth power ($\sigma \left[(t_h + 460/100)^4 - (t_c + 460/100)^4\right]$) in radiation heat transfer calculations for temperatures in and near the thermally neutral zone results in relatively small dependendence on temperature, and therefore the error is small.

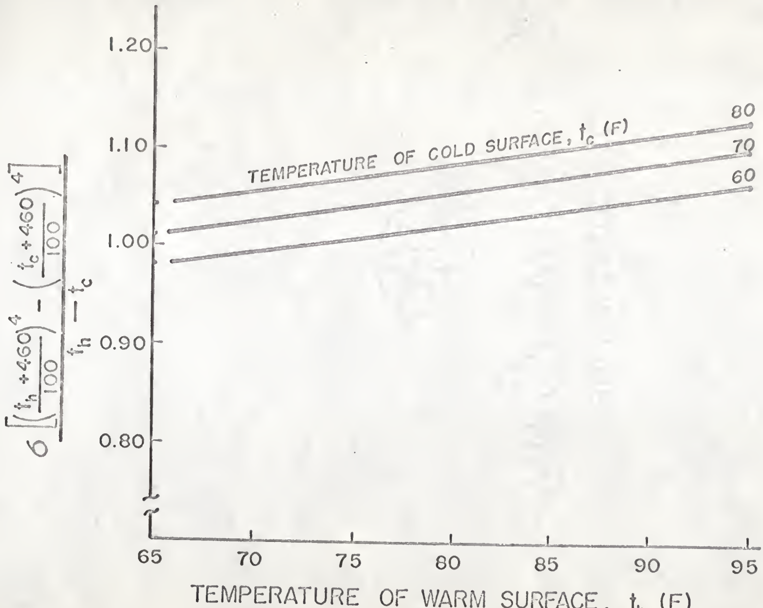

Figure F-1. The ratio of the differences of temperatures to the fourth power to linear differences of temperatures is shown as a function of temperature to demonstrate the accuracy of a linear approximation in radiation heat transfer calculations for normal room temperatures.

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THE RELATIVE EFFECTS OF CONVECTION
AND RADIATION HEAT TRANSFER ON
THE THERMAL SENSATIONS
OF SEDENTARY
SUBJECTS

by

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ABSTRACT

A study was conducted to determine the relative effects of convection and radiation heat transfer on the thermal sensations of sedentary subjects. A set of environments of eight combinations of mean radiant temperature (MRT) and air temperature were selected in and around the thermally neutral zone. Twenty college-age subjects (10 males, 10 females) were exposed to each environment for three hours. The subjects indicated their thermal sensations on a seven point ballot at each half hour. A regression analysis was performed on the mean vote of the last three ballots.

It was assumed that the same physical laws that govern radiation and convection heat loss from the subject to his environment also governs the effects of MRT and air temperature on the subject's "thermal sensation" response to his environment. The analysis therefore shows the relative influence of convection and radiation heat transfer, determined by the ratio of the convection heat transfer coefficient (h_C) to the radiation heat transfer coefficient (h_R), for sedentary people wearing clothes with an insulation value of approximately 0.60 clo in equilibrium with environments that have a partial pressure of water vapor of 0.435 in. Hg and a relative air velocity of 25-30 fpm to be:

1. Males (metabolic rate = 389 B/hr), $h_C/h_R = 1.51$
2. Females (metabolic rate = 301 B/hr), $h_C/h_R = 1.37$

3. Males and females combined (metabolic rate = 345 B/hr), h_C/h_R = 1.43, recommended value 1.4.

In addition, a zone of thermal neutrality is developed for combinations of MRT and air temperature. This represents environments such that the average thermal response for sedentary subjects is that they are neither too warm nor too cool.

VITA

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